HIGH AVERAGE POWER SEED LASER DESIGN FOR HIGH REPRATE FELs*

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Abstract

For two ultrashort pulse X-ray FEL designs, we show that seed or modulating lasers can be built using existing laser technology. An HGHG cascade FEL is seeded with UV from a high average power, frequency quadrupled OPCPA pumped by thin disk regenerative amplifiers. An E-SASE FEL has the electron bunch modulated by a single optical cycle at 2μm, generated by coherently added OPA signal and idler at 1.5 and 3μm.

INTRODUCTION

To be maximally useful as experimental sources X-ray FELs need to control the time-varying parameters of the pulse, that is, instantaneous amplitude and phase. This can be achieved by seeding the FEL with a light pulse generated by a laser or a combination of laser and optical harmonic generation systems. High gain harmonic generation (HGHG) can be used to extend the photon energy range of the FEL beyond that of the seed laser. It is also possible to make a temporally uniform pulse by using a laser to modulate the electron density, generating a current spike with a bandwidth equal to the FEL gain bandwidth, and allowing spontaneous emission during this shortened bunch to seed the FEL process. We have designed FELs using both these schemes [1, 2] and designed seed laser systems which can produce the needed optical pulses. This paper describes the laser designs.

HGHG SEED LASER

For the cascaded HGHG scheme, we seed with a UV pulse in the 220nm range, and multiply frequency in the FEL up to 600eV. Various multiplication factors can be chosen, but since they are integers, the seed laser must be tunable to cover gaps and allow quasi-continuous wavelength tuning. Thus a range of 217 to 261nm is needed. The pulse width range covers 100fs to 10fs, but with peak optical power of ~250MW at 100fs, up to 700MW at 10fs. At 100fs, the pulse energy is 25μJ, and at a repetition rate of 100kHz requires 2.5W at the FEL modulator. At 10fs, the pulse energy at the modulator is 7μJ, with 700mW.

We have initially designed two optical parametric chirped pulse amplifier (OPCPA) laser systems to address the short and long pulse requirements, as it may be difficult to cover the pulse width range with one amplifier setup. While it may be possible to hybridize the design, and at least use the same pumps for two systems, we can at least show that the extremes of the range can be generated. A diagram of the overall seed laser is shown in figure 1, with detail of the OPA amplifier for 100fs (power and energy worst case) shown in figure 2. Also shown in figure 2 are the spectral widths for the two designs).

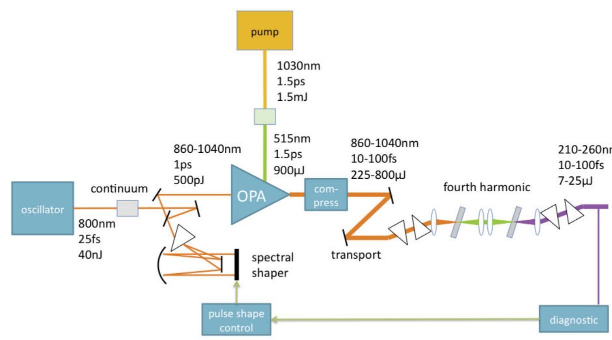

Figure 1: HGHG seed laser design. The diagram shows one of five pump lasers for the OPA.

OVERALL LASER DESIGN

In the seed laser, a titanium sapphire laser emits short (~20fs) pulses which are amplified and then broadened in a nonlinear element to produce a continuum in the 820-1100nm range. A broadband pulse shaper filters the continuum (according to which UV wavelength and pulse width is desired) and controls the spectral phase and amplitude of the resulting pulses, which are subsequently stretched to around 1ps. A five-stage OPA amplifies the stretched pulses to 790μJ (in the 100fs case), after which they are compressed by chirped mirrors [3] and frequency quadrupled to the ultraviolet (238nm in this calculation). Assuming 10% efficiency for fourth harmonic generation, and 30% transmission loss, there will be 24μJ at the FEL. For the 10fs case, 233μJ are needed from the amplifier, assuming the same FHG efficiency and loss).

PUMP LASER

To produce 800uJ at the OPA output, with 100kHz repetition rate, and nominal 20% OPA efficiency, a frequency doubled IR pump with about 400W is needed. With 60% efficient SHG, the IR power is 670W. There currently exist Yb:YAG thin disk regenerative amplifiers

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[4] with 150W output power, and 300W versions are being developed. These can be multiplexed by pumping successive OPA stages, with two 150W regens or one 300W regen powering the final OPA stage. A diagram of the thin disk regen is shown in figure 3. The disk amplifier is a version of the devices used in industrial materials processing lasers, taking advantage of the reliability of those systems.

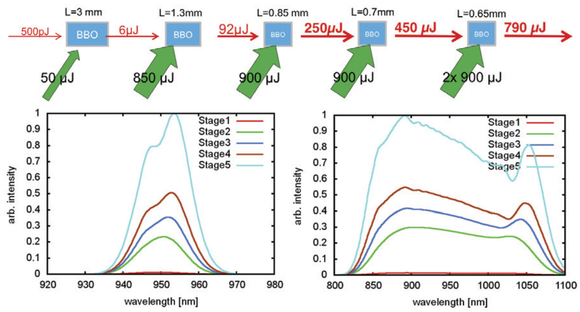

Figure 2: Upper figure: OPA staging and pump energies for the 100fs design. Lower figure: bandwidths for the 100fs and 10fs design, respectively.

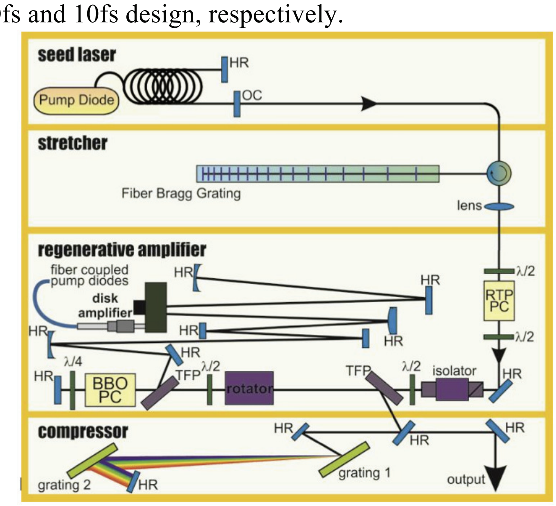

Figure 3: Thin disk regenerative CPA system.

E-SASE MODULATION LASER

A different laser would be used to generate a current spike in an E-SASE scheme [2]. A single optical cycle at 2 micron wavelength modulates the electron density within a bunch, producing a short current spike, which lases to produce an X-ray pulse 1 to 2fs in duration. A single optical cycle has ~100% fractional bandwidth, which is difficult to produce from one laser. Fortunately, the FEL process is highly nonlinear, allowing for significant energy in wings near the central cycle. Thus, a reduced bandwidth range can be used, as long as the time derivative of the e-field in the wings is 3 to 4 times less than in the peak. It is possible to produce such pulses with two, widely spaced optical bands of less than 25% fractional bandwidth each. Figure 4a shows two wavelength bands at 1.5 micron (18% bandwidth) and 3 micron (25% bandwidth) center wavelengths, which are added in phase to produce the pulse of figure 4b. This pulse has been used as an input to an FEL model, with the resultant X-ray output in figure 5. There is some lasing in the wings, but this level is acceptable.

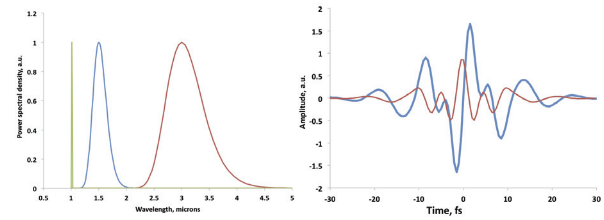

Figure 4: Left: wavelength bands of the signal (blue), idler (red) and pump (green). Right: electric field of added pulses (blue) and time derivative (red).

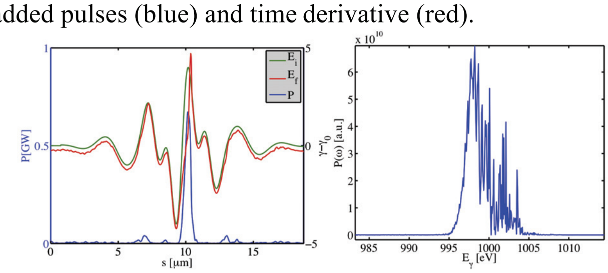

Figure 5: Left: Input and output slice energy variation(green and red respectively). X-ray power at 1keV (blue). Note small wings at high slope parts of the modulation. Power FWHM is 1.6fs. Right: output X-ray spectrum. The pulse is about 4.4 times transform limit.

SINGLE CYCLE IR LASER DESIGN

The wavelength bands of figure 4 were chosen so that the laser design of figure 6 could be used. Estimated performance is based on demonstrated NIR OPCPA lasers [5,6]. Here, an OPA is pumped by ~1 micron light, and produces a 1.5 micron signal and 3 micron idler (which is the difference frequency between the pump and signal). The signal begins with an erbium-doped fiber laser at 100fs, which is compressed to ~20fs in a first stage of compression. It is then amplified and chirped with enough bandwidth to be compressed again to 10fs. The pulse is stretched and spectrally shaped before being amplified in the OPA, which outputs equal power in the signal and idler. These signals are separately compressed and beam formed before being coherently added at the output to produce a single cycle.

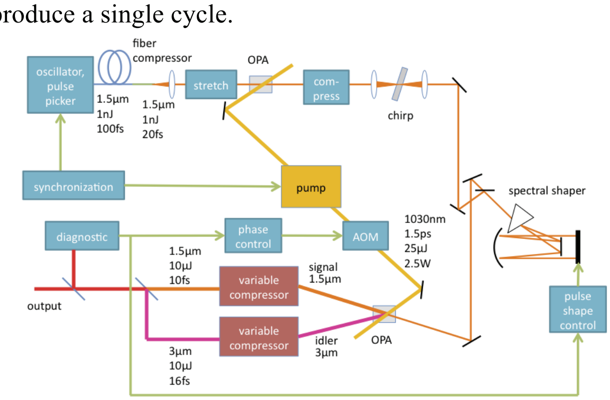

Figure 6: Single cycle IR laser design.

Since the idler is the difference frequency between pump and signal, its phase is the difference in phase between them. The original signal is carrier/envelope phase (CEP) stabilized, and acts as a reference (preserved through the compressors and amplifier). The pump is not CEP-stabilized, but the phase is controlled by an acousto-optic frequency shifter which is adjusted in response to a diagnostic (e.g. SPIDER, FROG) looking at the e-field of the single cycle combined pulse. The carrier/envelope offset frequency can be removed by the AOM such that the idler phase follows the signal phase, and they can be successfully added. Since the repetition rate of the pump is 100kHz, the frequency shifter need only shift the offset frequency by one 100kHz comb line before resetting, which is well within its bandwidth.

Peak power required for the E-SASE scheme is 800MW, although the short pulse duration of 6.7fs (one cycle at 2 microns) means only 5.3μJ are needed, at least in the central part of the pulse. There is about the same amount of energy in the wings, so the total is closer to 10μJ. This is comprised of an approximately equal contribution from the signal and idler, each of which is carrying ~20% of the pump power. This scheme is efficient because the idler is used, rather than being discarded as is typical. Also, in comparison to the HGHG seed described above, there are no frequency conversion stages in the signal or pump. Thus, neglecting losses, the IR pump would have to produce only 25μJ, or 2.5W at 100kHz. Broadband, low dispersion metallic mirrors used in the transport system could cause ~3% loss per reflection, and can distort the phase front if heating occurs, potentially reducing the optical power interacting with the electron beam. Pump power requirements may increase in order to make up for a variety of losses.

BEAM TRANSPORT

To minimize loss and excess dispersion in the HGHG seed transport system, fourth harmonic generation should be performed as near to the injection into the FEL as possible. In the 800 to 1100nm region, wide band, low loss, low dispersion (or specified dispersion) mirrors can be obtained more easily than for wavelengths near the vacuum ultraviolet. Thus, the FHG module, occupying around 1 cubic foot of volume, could be located in the FEL tunnel area, preferably shielded from radiation and aligned remotely.

As the single cycle signal for E-SASE is very broad band, small amounts of dispersion in transport optical components such as mirrors and windows can distort the pulse before it reaches the FEL. Gold mirrors have flat reflectivity and negligible dispersion across the required band, but near-infrared transmitting vacuum windows will have to be used to separate low and high vacuum sections of the optical path. If the differential pressure is minimized, very thin windows can be used. Still, differential compensation of the two bands will probably have to be performed using both compressors and the pump phase shifter, based on downstream diagnostics.

CONCLUSIONS

We have shown that laser designs realizable with current technology are able to meet the requirements of two promising FEL designs where temporal pulse parameters are controlled. Originally daunting average power in one case and large fractional bandwidth in the other have been made tractable by partitioning the parameter in question.

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